
# Development of a Science and Applications Traceability Matrix for the Mass Change Designated Observable

Focus Area: Climate Variability and Change

Community Telecon: Led by Carmen Boening[1] and David Wiese[1]

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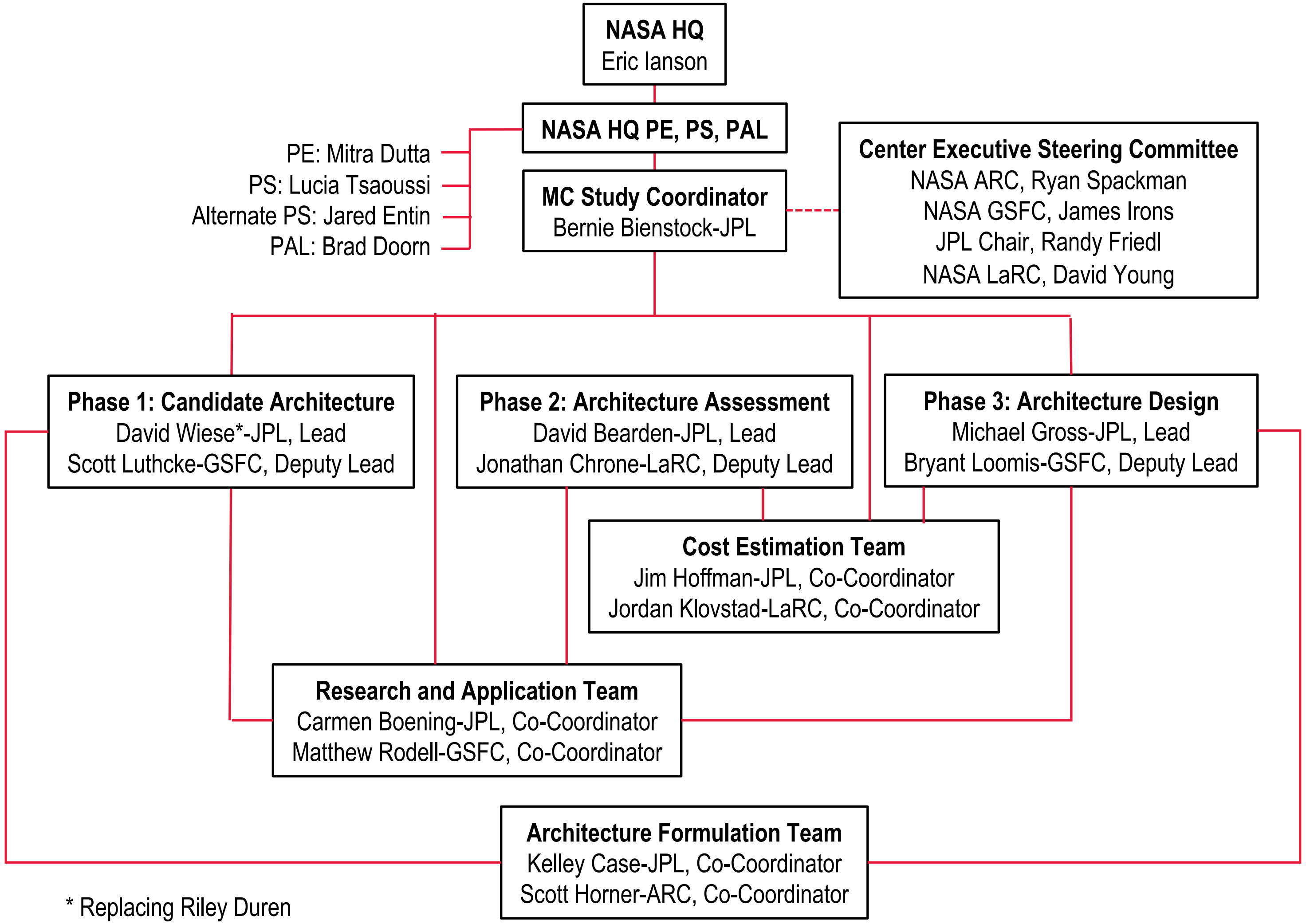
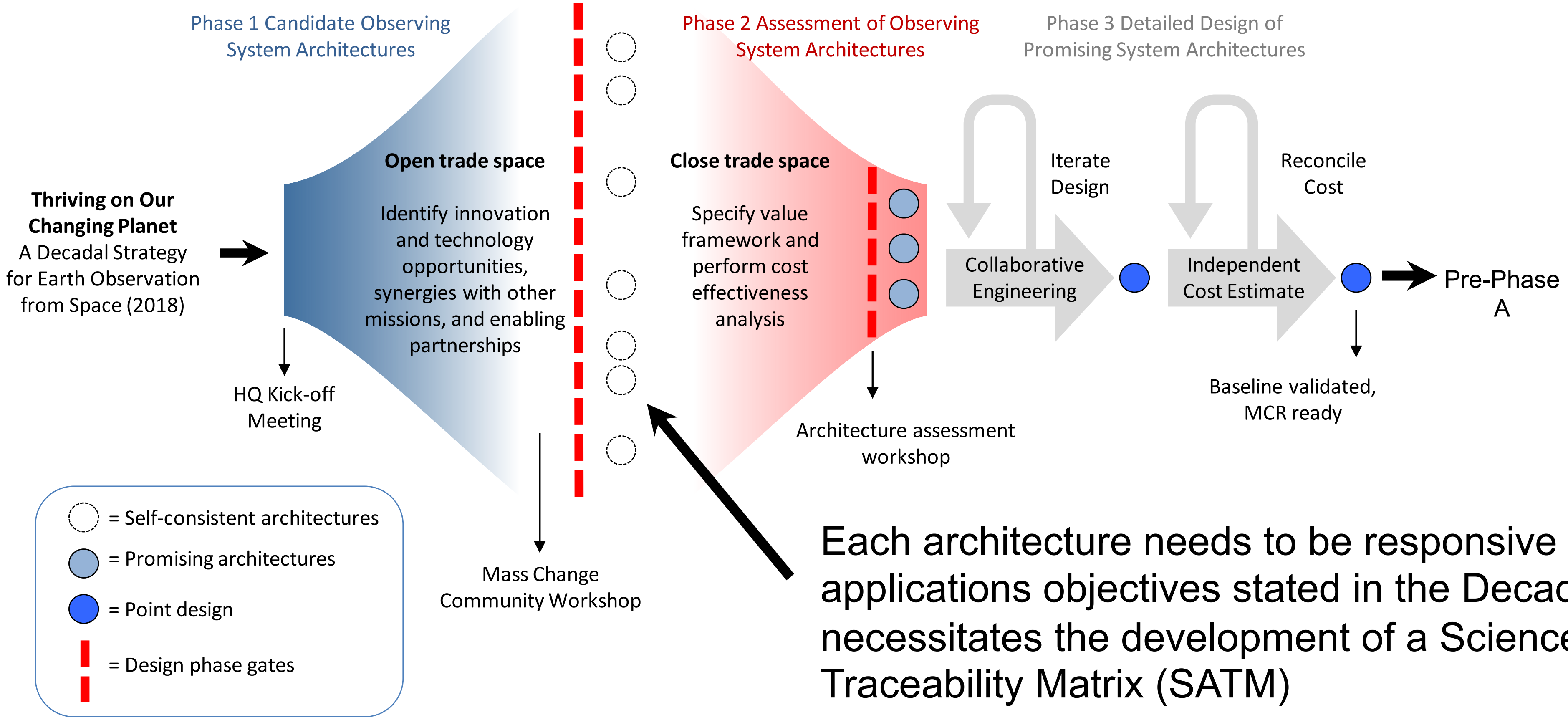
# Mass Change Study Background

- The 2017-2027 Decadal Survey listed Mass Change (MC) as one of five Designated Observables (DO)
- NASA initiated multi-center studies focused on each DO.
  - Mass Change: (JPL [lead], GSFC, LaRC, ARC)
- Mass Change Study Objectives:
  - Identify and characterize a diverse set of high value Mass Change observing architectures responsive to the Decadal Strategy report's scientific and application objectives for MC
  - Assess the cost effectiveness of each of the studied architectures
  - Perform sufficient in-depth design of up to three selected architectures to enable rapid initiation of a Phase A Study



# Study Phases




Each architecture needs to be responsive to the science and applications objectives stated in the Decadal Survey. This necessitates the development of a Science and Applications Traceability Matrix (SATM)

MC-DO SATM Working Group: Carmen Boening, Bryant Loomis, Scott Luthcke, Matt Rodell, Jeanne Sauber, Frank Webb, David Wiese, Victor Zlotnicki

# SATM Overview for Mass Change DO

**Creating Traceability from DS Science/Applications Objectives to Observing System Architectures**

- **Baseline** Observing System – supports full science objectives
- **Goal** Observing System – supports additional science with a goal to create longevity in the mass change time series. May include advancements of enabling technologies

Weighted DS Science/Application Objective → Necessary Geophysical Observables → Relative Importance of MC to meet DS Science/ Application Objective [Utility] → Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Baseline/Goal → Instrument Performance for various types of architectures

15 are Prescribed in DS; 6 for Climate Variability and Change

# Decadal Survey Science and Application Objectives for Mass Change

## A Diverse Set of Objectives Spanning Three Panels

**Climate Variability and Change**

- C-1a: Global Sea Level
- C-1c: Ice Sheet Mass Change
- C-1b: Ocean Heat
- C-7d: Dynamical Ocean State
- C-1d: Regional Sea Level
- C-7e: Ocean Circulation

**Global Hydrological Cycles and Water Resources**

- H-1a: Water Balance Closure
- H-2c: Groundwater Recharge
- H-3b: Water Availability & Storage
- H-4c: Drought Monitoring

**Earth Surface and Interior**

- S-1b: Earthquakes
- S-4a: Landscape Changes
- S-3a: Glacial Isostatic Adjustment/Local Sea Level
- S-5a: Earth Energy Flow
- S-6b: Groundwater Flux

→ Science Performance Targets

**DS Prescribed Weights [Importance]**

- Most Important, Highest weight
- Very Important, Medium weight
- Important, Lower Weight

# MC Interpretation of DS Objectives

Weighted DS Science/Application Objective

Necessary Geophysical Observables

**Value Judgment: Requires Community Vetting**

Relative Importance of MC to meet DS Science/Application Objective [Utility]

Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Baseline/Goal

Instrument Performance for various types of architectures

# Community Workshop Feedback

- Community Workshop held in Washington DC July 30 - Aug 1
- Well attended with ~80 participants
- Conducted breakout sessions dedicated to each discipline with a primary focus to get and incorporate feedback into the SATM
  - Climate Variability and Change
  - Global Hydrological Cycles and Water Resources
  - Earth Surface and Interior
- **Consistent themes in each breakout session did emerge**
  - Baseline Performance should be equivalent to current data record
  - Continuity (minimizing the length of any gap after the end of life of GRACE-FO to the extent possible) and a long data record are of primary importance
  - These **reaffirmed the recommendations** expressed in the Decadal Survey regarding performance and continuity for mass change
- Breakout groups tackled each DS Science Objective separately

# Suggested Measurement Parameters for Baseline

**Weighting Combines DS Weights with MC Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height**

## Climate Variability and Change

- C — C-1a: $(300\text{ km})^2$; 15 mm Monthly — O (Highest Weight)
- C — C-1c: $(300\text{ km})^2$; 40 mm Monthly — I (Highest Weight)
- C — C-1b: $(300\text{ km})^2$; 15 mm Monthly — O (Highest Weight)
- C — C-7d: $(300\text{ km})^2$; 15 mm Monthly — O (Low Weight)
- C — C-1d: $(300\text{ km})^2$; 15 mm Monthly — O (Medium – High Weight)
- C — C-7e: $(300\text{ km})^2$; 15 mm Monthly — O (Low Weight)

## Global Hydrological Cycles and Water Resources

- H-1a: $(1000\text{ km})^2$; 10 mm Monthly — L (Highest Weight)
- H-2c: $(450\text{ km})^2$; 25 mm Monthly — L (Highest Weight)
- H-3b: $(450\text{ km})^2$; 25 mm Monthly — L (Medium Weight)
- C — H-4c: $(450\text{ km})^2$; 25 mm Monthly — L (Medium-Low Weight)

## Earth Surface and Interior

- S-1b: $(300\text{ km})^2$; 25 mm Monthly — G (Highest Weight)
- S-3a: $(300\text{ km})^2$; 25 mm Monthly — G (Highest Weight)
- S-4a: $(300\text{ km})^2$; 25 mm Monthly — G (Medium – High Weight)
- S-5a: $(20{,}000\text{ km})^2$; 1 mm Monthly — G (Medium-Low Weight)
- S-6b: $(450\text{ km})^2$; 25 mm Monthly — L (Medium-Low Weight)

Science Performance Targets

C: Continuity explicitly recommended in Decadal Survey

Highest Weight | Medium – High Weight | Medium Weight | Medium-Low Weight | Low Weight

G: Global
O: Ocean
L: Land
I: Ice

# Suggested Measurement Parameters for Goal

**Weighting Combines DS Weights with MC Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height**

## Climate Variability and Change

- C — C-1a: (100 km)$^2$; 15 mm; Monthly — O
- C — C-1c: (100 km)$^2$; 10 mm; Monthly — I
- C — C-1b: (100 km)$^2$; 15 mm; Monthly — O
- C — C-7d: (50 km)$^2$; 10 mm; Monthly — O
- C — C-1d: (100 km)$^2$; 15 mm; Monthly — O
- C — C-7e: (50 km)$^2$; 10 mm; Monthly — O

## Global Hydrological Cycles and Water Resources

- H-1a: (3 km)$^2$; 10 mm; Monthly — L
- H-2c: (50 km)$^2$; 10 mm; Monthly — L
- H-3b: (200 km)$^2$; 25 mm; Monthly — L
- C — H-4c: (50 km)$^2$; 1.5 mm; Weekly — L

## Earth Surface and Interior

- S-1b: (200 km)$^2$; 12 mm; Monthly — G
- S-4a: (200 km)$^2$; 12 mm; Monthly — G
- S-3a: (200 km)$^2$; 10 mm; Monthly — G
- S-5a: (20,000 km)$^2$; .01mm; Monthly — G
- S-6b: (100 km)$^2$; 10 mm; Monthly — L

C: Continuity explicitly recommended in Decadal Survey

Highest Weight | Medium – High Weight | Medium Weight | Medium-Low Weight | Low Weight

G: Global
O: Ocean
L: Land
I: Ice

**Science Performance Targets**

# Linking Architectures to Science Performance

Weighted DS Science/Application Objective

Necessary Geophysical Observables

Relative Importance of MC to meet DS Science/Application Objective [Utility]

Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Baseline/Goal

Instrument Performance for various types of architectures

**Will be Populated in Phase 2**

**We have expanded an OSSE capability to link architectures to DS Science Objectives from which we can quantitatively determine science value**

# Quantitatively Determining Science Value

$$SV(a) = \sum_{n=1}^{15} (W_n) P_n = \sum_{n=1}^{15} \left( W_n \frac{Spatial\_Resn}{Spatial\_Res(a)} \frac{Temporal\_Resn}{Temporal\_Res(a)} \frac{Accuracy_n}{Accuracy(a)} \right)$$

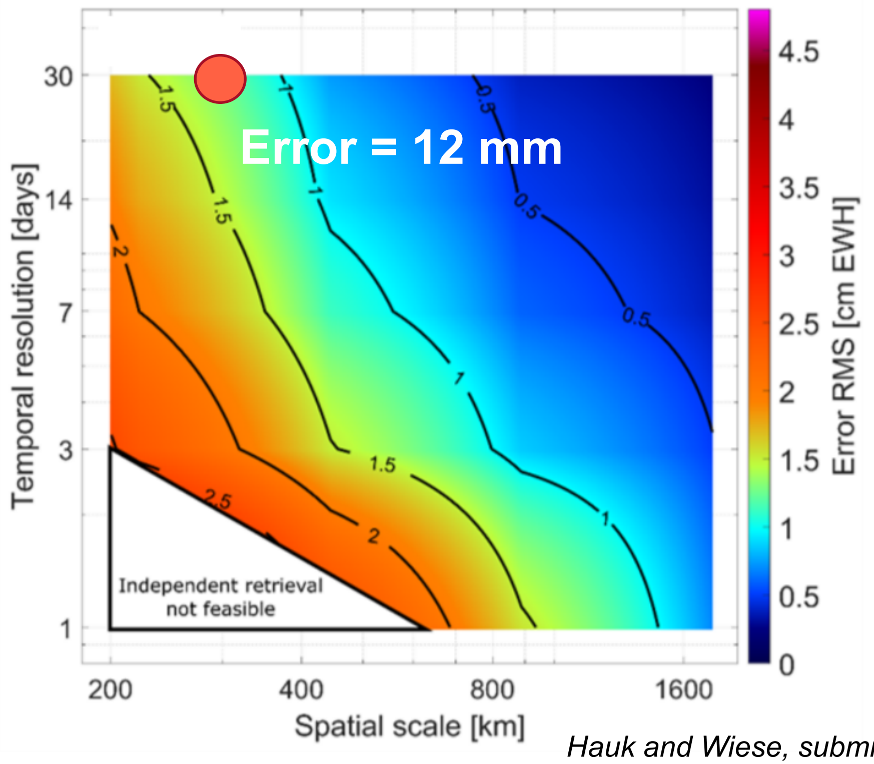
Science Objective *n*

C-1a:
(300 km)$^2$; **15 mm**
Monthly

Highest Weight

W = Importance * Utility = 1

Architecture *a*




*Hauk and Wiese, submitted.*

$SV_n = 1 * 15/12 = 1.25$

# Decadal Survey: Climate Variability

TABLE C.1 (Continued)

| Targeted Observable | Science and Applications Summary | Science/Applications Priorities by Panel[a] | | | |
|---|---|---|---|---|---|
| | | | MI | VI | I |
| TO-9<br><br>Mass Change | · Groundwater and water storage mass change<br>· Land-ice mass change<br>· Ocean mass change<br>· Glacial isostatic adjustment<br>· Earthquake mass movement | H | 1a, 2c | | 3b, 4c |
| | | W | | | |
| | | E | | | |
| | | C | 1a, 1b, 1c | 1d | 7d, 7e |
| | | S | 1b, 3a, 4a | 5a | 6b |

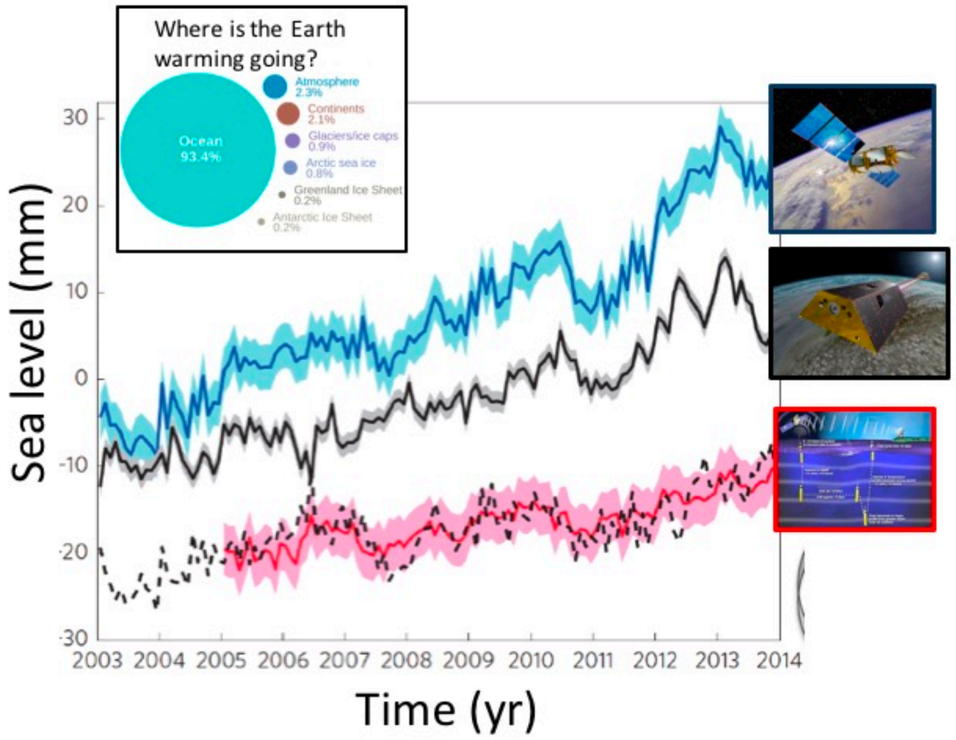
| Related ESAS 2007 and POR | Identified Need/Gap | Candidate Measurement Approach | ESAS 2017 Disposition |
|---|---|---|---|
| *ESAS 2007:* GRACE-II<br><br>*POR:* GRACE, GRACE-FO | POR does not include coverage after GRACE-FO | ***Similar to:* GRACE**<br>· Measurement of gravity anomaly with spatial resolution of 200 km at the equator (goal of 50 km or less) | **DESIGNATED**<br>PROGRAM ELEMENT<br><br>Maximum development cost $300 million; ensure continuity after GRACE-FO |

# Decadal Survey: Climate Variability

- Page 126: The need to quantify the rates of sea-level change and its driving processes at global, regional, and local scales is of great importance as discussed by the Climate Panel. Quantifying and understanding sea level changes requires use of several satellite-based instruments including using radar altimeters over the oceans, and radar and laser altimeters over the ice sheets, along with GPS, InSAR, and GRACE gravity measurements. Gravity measurements not only provide critical information on the contributions of ice sheets and glacier systems to sea level rise, but also changes and movement of mass throughout the Earth.
- Page 147: Ensures continuity of measurements of ground water and water storage mass change, land ice contributions to sea level rise, ocean mass change, ocean heat content (when combined with altimetry), glacial isostatic adjustment, and earthquake mass movement. Also important for operational applications, including drought assessment and forecasting, hazard response and planning water use for agriculture and consumption Addresses various “Most Important” objectives of the Climate, Hydrology, and Solid Earth panels

# Decadal Survey: Climate Variability

- QUESTION C-1. How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?




$$H_{total}=H_{steric}+\boldsymbol{H_{mass}}$$

*Key points:*

- Long time series are key – lifetime of architecture above increasing resolution for sea level budget on global and even regional level
- Interannual fluctuations influence trend and acceleration estimates – hence long gaps influence our ability to estimate those
- Science objectives should reflect constraints on observing system and not include the ability to do vertical disaggregation/separation of mass change signals

# Performance Targets Derived from Community Interpretation: C1-a

DS Science Objective – C-1a
[MOST IMPORTANT]

C-1a. Determine the global mean sea level rise to within 0.5 mm yr-1 over the course of a decade

**Necessary Observables**

Sea surface height
Terrestrial reference frame
Ocean mass distribution

**Relative Importance of MC [Utility]**

High. MC provides a unique measurement of global ocean mass change

**Performance Targets**

Baseline
$(300\ \text{km})^2$; 15 mm EWH, Monthly

Goal
$(100\ \text{km})^2$; 15 mm EWH, Monthly

Key measurement parameter is underlined

**Community interpretation and justification for performance target**

Baseline: Specified in DS Appendix B

Goal: Higher spatial resolution will reduce land leakage errors which are one of the dominant sources of error in determining global ocean mass.)

# Performance Targets Derived from Community Interpretation: C-1d

DS Science Objective C-1d
[VERY IMPORTANT]

C-1d. Determine regional sea level change to within 1.5- 2.5 mm/yr over the course of a decade (1.5 corresponds to a ~6000-km2 region, 2.5 corresponds to a ~4000-km2 region)

| Necessary Observables | Relative Importance of MC [Utility] | Performance Targets |
|---|---|---|
| Sea surface height<br>Vertical land motion<br>Ocean mass distribution<br>Wind vector | High. MC provides a unique measurement of ocean mass change | Baseline<br>(300 km)$^2$; 15 mm; Monthly<br><br>Goal<br>(100 km)$^2$; 15 mm; Monthly |

Key measurement parameter is underlined

**Community interpretation and justification for performance target**

Baseline: Specified in DS Appendix B

Goal: Higher spatial resolution will reduce land leakage errors which are one of the dominant sources of error in determining global ocean mass.)

# Performance Targets Derived from Community Interpretation: C-1b

DS Science Objective C-1b
[MOST IMPORTANT]

C-1b. Determine the change in the global oceanic heat uptake to within 0.1 Wm-2 over the course of a decade

**Necessary Observables**

Sea surface height
Ocean mass distribution
Ocean temp and salinity profile

**Relative Importance of MC [Utility]**

High. Ocean heat uptake is related to total minus mass component. Serves as independent measurement of planetary heat uptake

**Performance Targets**

Baseline
(300 km)$^2$; 15 mm EWH; Monthly

Goal
(100 km)$^2$; 15 mm EWH; Monthly

Key measurement parameter is underlined

## Community interpretation and justification for performance target

Baseline: Specified in DS Appendix B

Goal: Higher spatial resolution will reduce land leakage errors which are one of the dominant sources of error in determining global ocean mass.)

*(1 mm/yr corresponds to 0.75 W/m2)*

# Performance Targets Derived from Community Interpretation: C1-c

DS Science Objective – C-1c
[MOST IMPORTANT]

C-1c. Determine the changes in total ice sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come

**Necessary Observables**

Ice sheet mass
Ice sheet velocity
Ice sheet elevation
Ice sheet thickness, ice shelf thickness
Ice sheet bed elevation, ice shelf cavity shape
Ice sheet surface mass balance

**Relative Importance of MC [Utility]**

High. Ice sheet mass change is directly measured through MC

**Performance Targets**

Baseline
$(300\ \text{km})^2$; 40 mm; Monthly

Goal
$(100\ \text{km})^2$; 10 mm; Monthly

Key measurement parameter is underlined

**Community interpretation and justification for performance target**

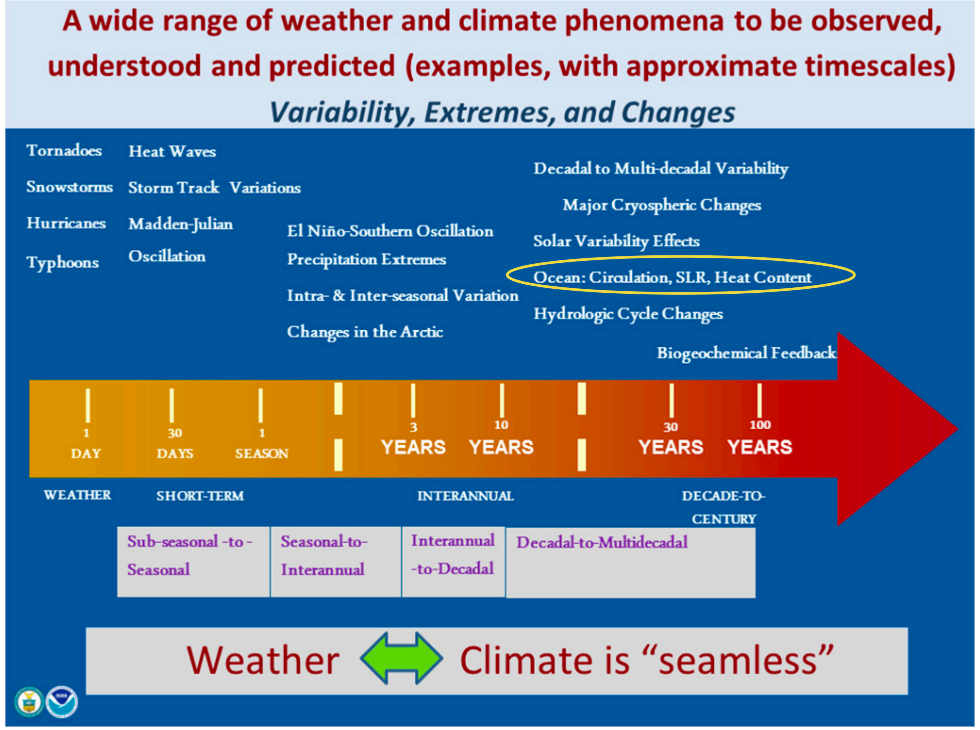
Baseline: Consistency with program of record

Goal: Higher spatial resolution to resolve glacier outlets for separation of drainage basins

Pail et al, 2015, Bonin and Chambers, 2015

# Decadal Survey: Climate Variability

- QUESTION C-7. How are decadal scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?




*Key points:*

- Key science: deep/mean circulation; oceanic transports
- Advantage of satellite observations: long time series, more reliable trends
- Resolution issue for resolving fronts and flow along topographic features
- Low signal requires consideration of low noise architectures
- **Ocean bottom pressure low contribution to science objective**

# Performance Targets Derived from Community Interpretation: C-7d

DS Science Objective C-7d
[IMPORTANT]

C-7d. Quantify the linkage between the <u>dynamical</u> and thermodynamic state of the <u>ocean</u> upon atmospheric weather patterns on decadal timescales. Reduce the uncertainty by a factor of 2 (relative to decadal prediction uncertainty in IPCC 2013). Confidence level: 67% (likely).

**Necessary Observables**

Ocean velocity, temperature, salinity, wind stress

<u>Ocean bottom pressure</u>

**Relative Importance of MC [Utility]**

Low. Mass change is a secondary observable for this objective.

**Performance Targets**

Baseline
<u>(300 km)</u>$^2$; 15 mm; Monthly

Goal
<u>(50 km)</u>$^2$; 10 mm; Monthly

Key measurement parameter is <u>underlined</u>

**Community interpretation and justification for performance target**

<u>Baseline:</u> Consistency with the current Program of Record

<u>Goal:</u> Specified in the Decadal Survey (Appendix B)

# Performance Targets Derived from Community Interpretation: C-7e

**DS Science Objective C-7e [IMPORTANT]**

C-7e. Observational verification of models used for climate projections. Are the models simulating the observed evolution of the large scale patterns in the atmosphere and ocean circulation, such as the frequency and magnitude of ENSO events, strength of AMOC, and the poleward expansion of the sub-tropical jet (to a 67% level correspondence with the observational data)?

**Necessary Observables**

Ocean velocity, temperature, salinity, wind stress

Ocean bottom pressure

**Relative Importance of MC [Utility]**

Low. Mass change is a secondary observable for this objective.

**Performance Targets**

Baseline
(300 km)$^2$; 15 mm; Monthly

Goal
(50 km)$^2$; 10 mm; Monthly

Key measurement parameter is underlined

**Community interpretation and justification for performance target**

Baseline: Consistency with the current Program of Record

Goal: Specified in the Decadal Survey (Appendix B)

# Upcoming Mass Change Community Events

1. **M**ass **C**hange Designated Observables Study AGU Town Hall

The MC study team will host a Mass Change Designated Observables Study Town Hall at the **AGU 2019 Fall Meeting on Thursday, Dec. 12,** from **12:30-1:30** p.m. (PT). Details are available on the AGU website.

2. **Gap-Impact Studies**. We would like your feedback/analysis of what length of gap would be tolerable to still meet the DS science objectives, if any. Please send any feedback to Carmen and/or David.

THANK you for joining us today. If you have further comments or questions please contact:

Carmen (Carmen.Boening@jpl.nasa.gov) or

David (David.N.Wiese@jpl.nasa.gov)

# BACKUP

# Other Useful Documents


- Visser, P., S. Bettadpur, D. Chambers, M. Diament, T. Gruber, E. Hanna, M. Rodell, and D. Wiese (2016). Towards a sustained observing system for mass transport to understand global change and to benefit society, Report of the NASA/ESA Interagency Gravity Science Working Group, Doc. nr. TUD-IGSWG-2016-01.
- Pail, R., Bingham, R., Braitenberg, C., Dobslaw, H., Eicker, A., Güntner, A., Horwath, M., Ivins, E., Longuevergne, L., Panet, I. and Wouters, B. (2015). Science and user needs for observing global mass transport to understand global change and to benefit society. Surveys in Geophysics, 36(6), pp.743-772.
- Bonin, J. A. and Chambers, D. P.: Quantifying the resolution level where the GRACE satellites can separate Greenland's glacial mass balance from surface mass balance, The Cryosphere, 9, 1761–1772, https://doi.org/10.5194/tc-9-1761-2015, 2015.

# GRACE-FO SATM

Science Objective

Primary science: Estimate gravity field and changes in time arising from mass distribution and mass transport within the Earth System due to climatic, tectonic, or anthropogenic forces. Apply monthly high resolution gravity measurements to derive comprehensive assessments of ice sheet mass balance, changes in underground aquifer storage, ocean circulation, lithospheric displacements from earth quakes and glacial isostatic adjustments.

Relevant Mass Change Observables for Threshold, Baseline, ~~and Goal~~ for:

1) Measurement System Performance
~~2) Science Performance~~

Instrument Performance ~~for various classes of architectures~~

# GRACE-FO traceability

**Secondary science:** Produce globally distributed atmospheric refractivity profiles to support improvements in weather, climate and ionospheric predictions

**Primary science:** Estimate gravity field and changes in time arising from mass distribution and mass transport within the Earth System due to climatic, tectonic, or anthropogenic forces. Apply monthly high resolution gravity measurements to derive comprehensive assessments of ice sheet mass balance, changes in underground aquifer storage, ocean circulation, lithospheric displacements from earth quakes and glacial isostatic adjustments.

**Long Term Mean Model** characterize the long term mean geopotential model, characterized by spherical harmonic to degree and order 150 or higher.

**Temporal Variability** characterize the temporal variability by sets of average values, over 30 days or longer, of the geopotential coefficients to spherical harmonic to degree and order 70 or higher with an equivalent root mean square geoid height measurement system error consistent with Table 3.1-1

**Observations**

- Ka-band range
- LRI range
- Accelerometer
- Star Camera
- GPS

**Spacecraft/Orbit**

- N sats
- Orbit
- Separation

**Analysis**

**Orbit Determ, Param estimation**

| Measurement | Product | Sample Rate |
|---|---|---|
| K-Band Ranging | Biased Range & Derivatives | 5 s |
| GPS Occultation | SNR + Phases | 50 Hz |
| Laser Ranges to satellite | Ground to GRACE distance (2-way) | 5 s |
| Satellite Position & Velocity | | 5 s |
| Acceleration | | 5 s |
| SCA Quaternions | | 5 s |
| GPS Ionosphere Occultation | SNR + Phases | variable |

**Gravity field estimation**

| Measurement | Product | Sample Rate |
|---|---|---|
| Geopotential Field | Spherical Harmonic Coefficients | 30 days or longer |
| Satellite Position & Velocity | Cartesian | 5 s |
| Excess Delay/Refractivity | Profiles | < 50 Hz |
| Temperature/Water vapor | Profiles | < 50 Hz |

**Input Models**
Gravity Model
GPS satellite orbits/clocks
Ka-boresight Vectors
High frequency Mass Variation

**Measurement System errors**

| Harmonic Degree | Geoid Height Error per Degree (mm) | Geoid Height Error Cumulative, from n=3 (mm) |
|---|---|---|
| n=2 | <0.10 | - |
| $2 < n \leq 10$ | <0.01 | <0.02 |
| $10 < n \leq 70$ | <0.15 | <0.40 |
| $70 < n \leq 100$ | <1.50 | <3.50 |
| $100 < n \leq 150$ | <65.0 | <200 |

# Mass Change Observables

Weighted* DS Science/Application Objective

Necessary Observables

Relative Importance of MC to meet DS Science/Application Objective

Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Threshold/Baseline/Goal

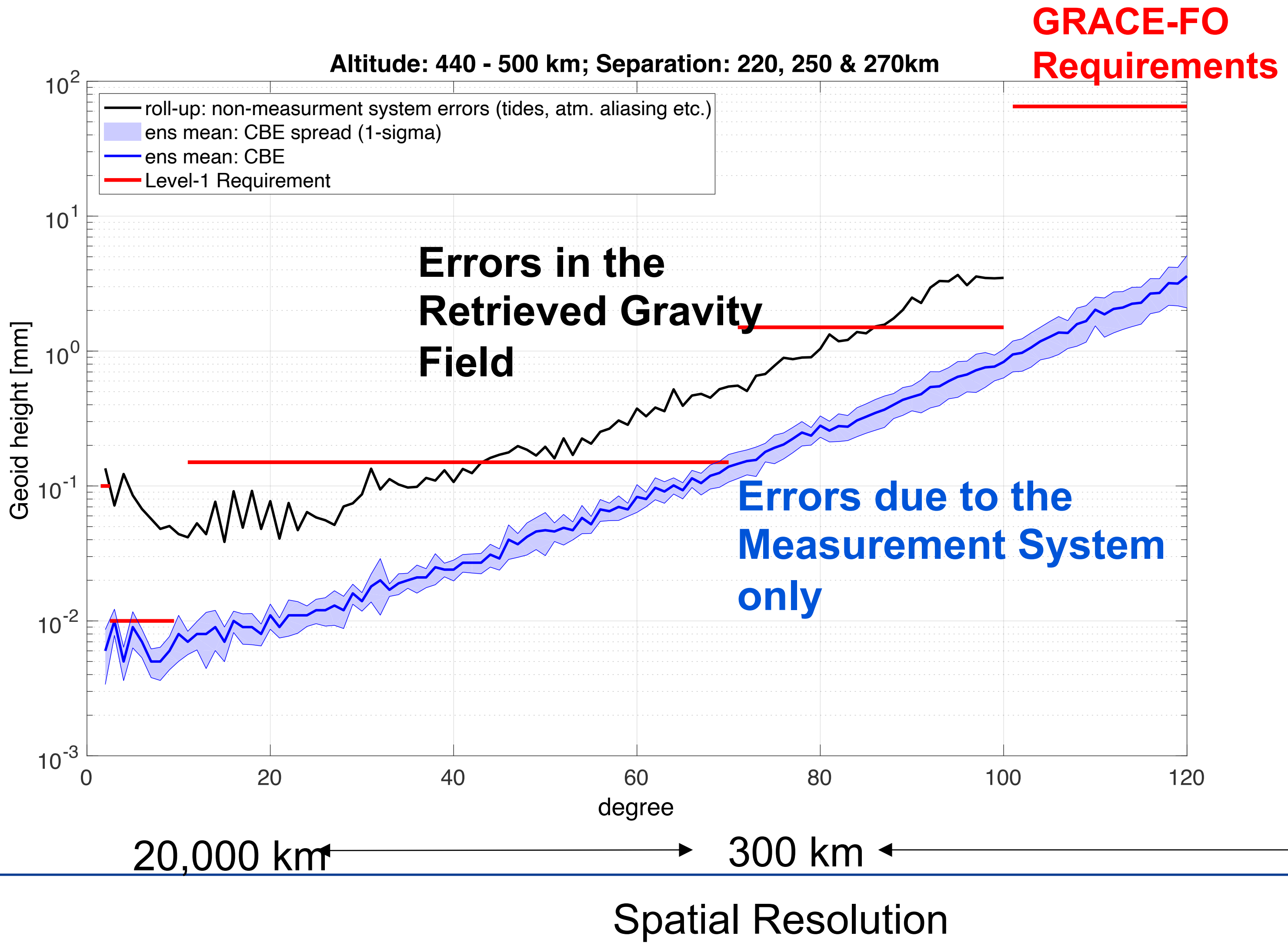
Relevant Mass Change Observables for Threshold, Baseline, and Goal for:

1) Measurement System Performance
2) Science Performance

Instrument Performance for various classes of architectures

**Driven by Community Input**

# Gravity Field Errors vs Measurement System Errors



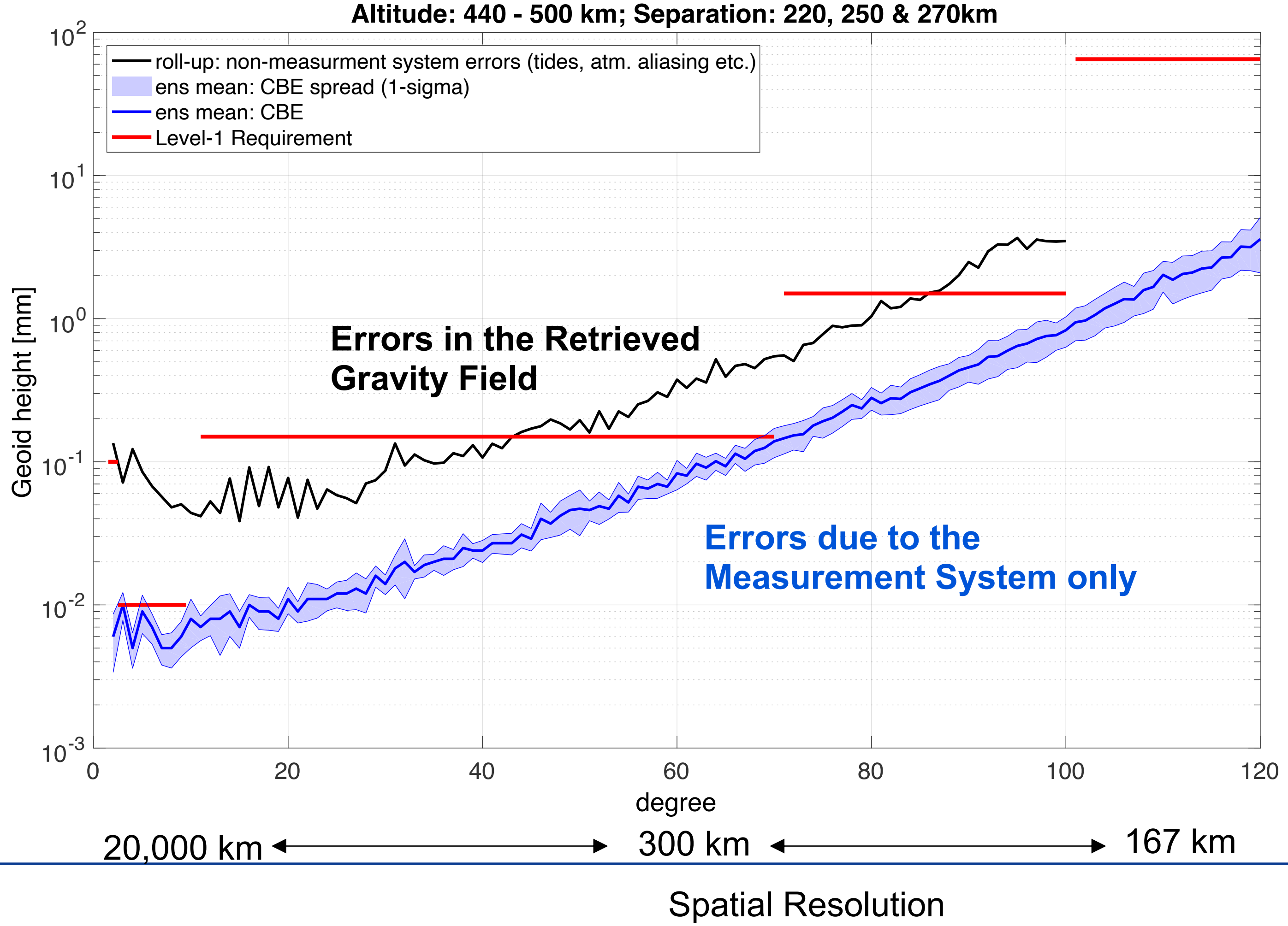

In the current state of the art (GRACE-FO), the gravity fields are not limited by the onboard measurement system: rather they are limited by our inability to model high frequency mass variations with periods < 1 month (ocean tides, atmospheric and oceanic mass variations).

Future data reprocessing has the potential to improve the gravity fields down to the limit of the measurement system.

# GRACE-FO Gravity Errors vs Measurement only errors

For GRACE-FO, requirements were placed solely on the measurement system. For MC-DO, we define two sets of targets:

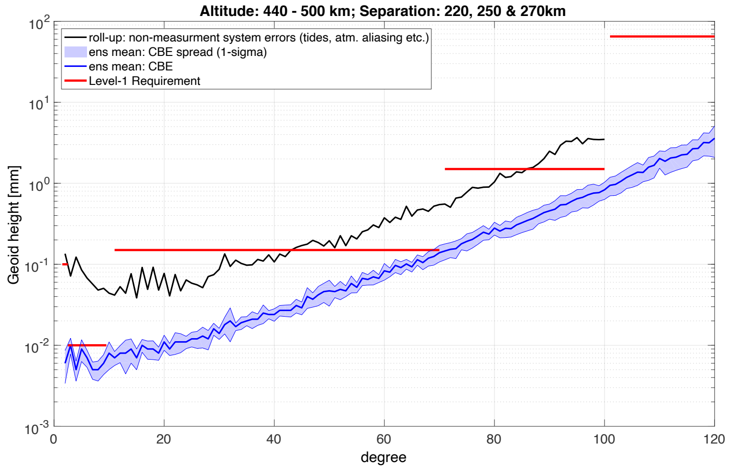
1) On the measurement system
2) On the retrieved gravity fields



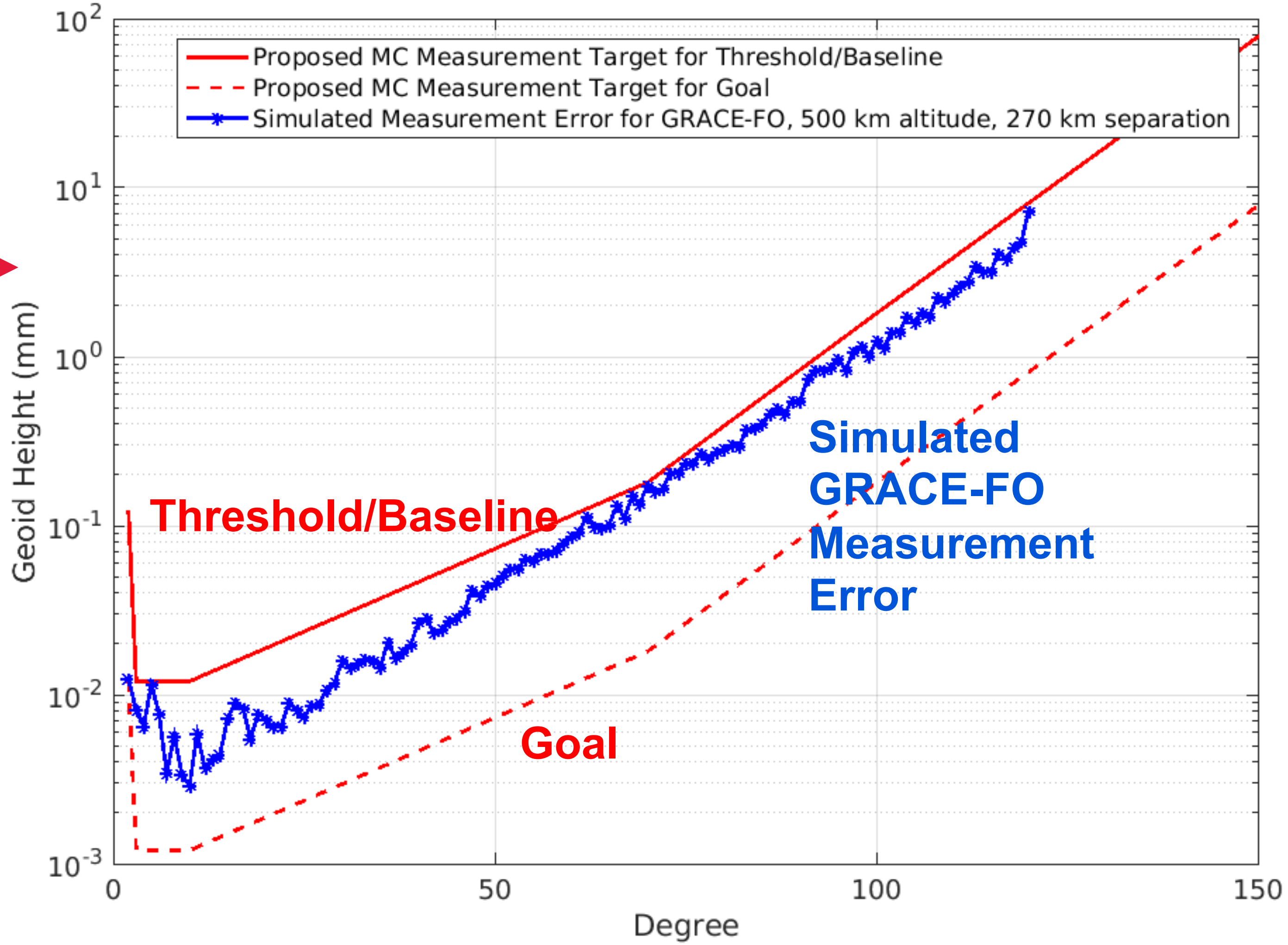

In the current state of the art (GRACE-FO), the gravity fields are not limited by the onboard measurement system: rather they are limited by our inability to model high frequency mass variations with periods < 1 month (ocean tides, atmospheric and oceanic mass variations).

Future data reprocessing has the potential to improve the gravity fields down to the limit of the measurement system.

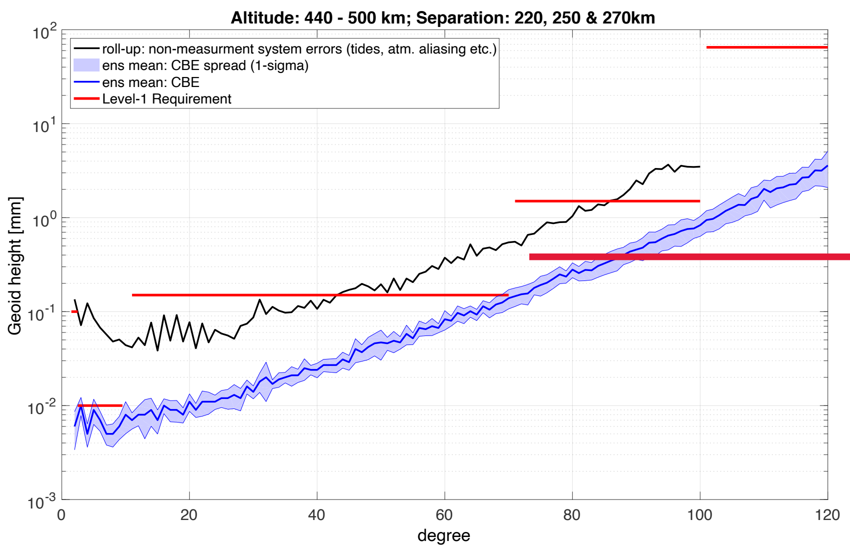
# Measurement System Performance Targets



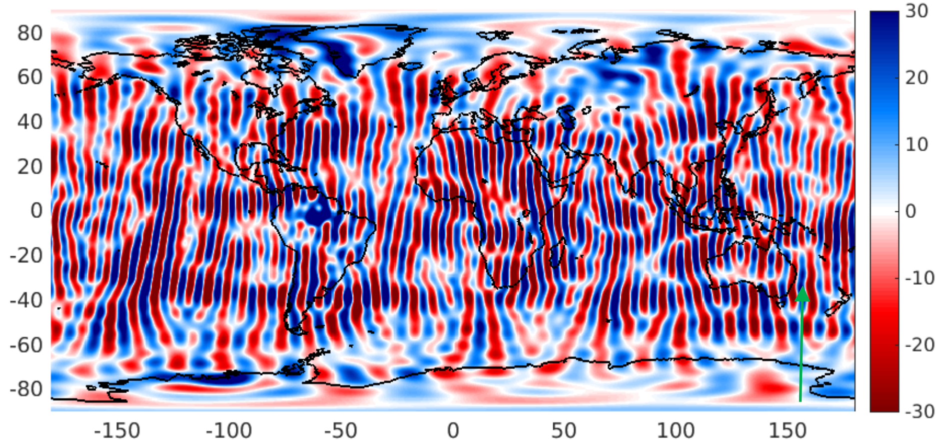

Proposed MC-DO Measurement Performance Targets



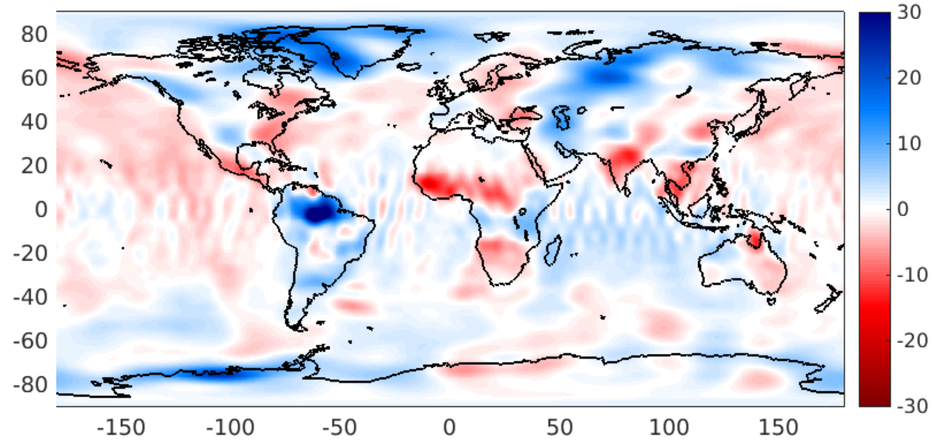
# Science Performance Targets




Raw Errors



Postprocessing



Science Performance Targets are written on this field

Our definition of science performance targets allows for the inclusion of post-processing algorithms. This approach allows for a more realistic assessment of science value.

# Relevant Mass Change Observables

## To Do: Review Science Performance Language

- Measurement System Performance:

  <u>Threshold and Baseline</u>

  <= 30-day average values of the geopotential coefficients to spherical harmonic degrees <=150 with equivalent room mean square geoid height error due to the measurement system errors are below that seen in the solid blue line in Figure 1.

  <u>Goal</u>

  <= 30-day average values of the geopotential coefficients to spherical harmonic degrees <=150 with equivalent room mean square geoid height error due to the measurement system errors are below that seen in the dashed blue line in Figure 1.

- Science Performance:

  <u>Threshold and Baseline</u>

  When considering both measurement system and systematic errors due to temporal aliasing, the architecture, including optimized data processing and filtering choices, shall be capable of recovering global monthly mass variations (the average of modeled hydrologic, oceanic, and cryospheric mass variations) at 300 km spatial scales with an accuracy of 40 mm [TBR] equivalent water height. A baseline reference for temporal aliasing errors is prescribed by Dobslaw et al., 2016 for non-tidal atmosphere and ocean mass variability and the difference between the FES2014 and GOT4.7 ocean tide models for mass variability from ocean tides.

  <u>Goal</u>

  When considering both measurement system and systematic errors due to temporal aliasing, the architecture, including optimized data processing and filtering choices, shall be capable of recovering global monthly mass variations (the average of modeled hydrologic, oceanic, and cryospheric mass variations) at 200 km spatial scales with an accuracy of 20 mm [TBR] equivalent water height. A baseline reference for temporal aliasing errors is prescribed by Dobslaw et al., 2016 for non-tidal atmosphere and ocean mass variability and the difference between the FES2014 and GOT4.7 ocean tide models for mass variability from ocean tides.

# Minimizing Data Gaps after GRACE-FO

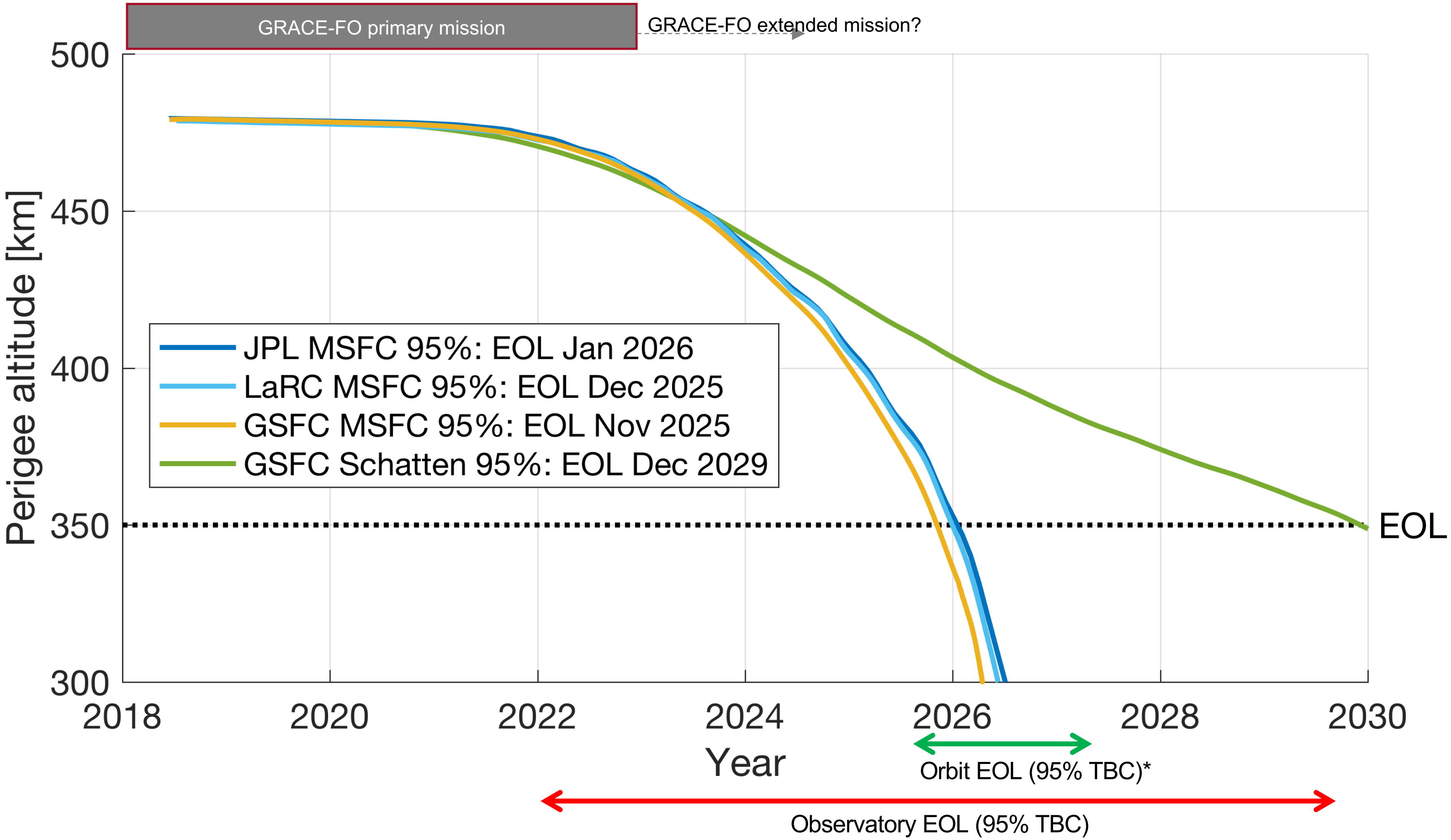
- A strong desire for a **long data record and minimizing any potential data gap** between GRACE-FO and an MC-DO was expressed at the community workshop.  This exceeded all other priorities and was agreed upon by all scientific disciplines
- Fundamentally, there is no need for inter-mission calibration, because we measure the full gravitational field. There is no bias between missions → hence the success of GRACE-FO (1-year gap after GRACE)
- Having **overlap between missions is the best form of calibration/validation** for MC due to the uniqueness of the measurement
- Having overlap becomes more important for architectures that differ significantly from GRACE-FO should the structure of the error be different.  A gap could affect consistency in the mass change data record for instance.
- Long* (*still to be defined) data gaps could affect the ability to estimate decadal trends because of interannual variability in the Earth's climate system
- The full impact of any gap on science/applications is still being assessed by the community
- **Continuity is not part of the SATM but should be a programmatic target for evaluation of options in phase 2** (because some options will have higher maturity and lower development risk/shorter schedule than others).

# Proposed Continuity Targets

- Proposed continuity targets
  - Threshold Continuity Objective: the MC-DO gravity field data product should at least meet the GRACE-FO Threshold science requirements on spatial/temporal resolution and accuracy with any gap between GRACE-FO and MC-DO not to exceed 12 months.*
  - Baseline Continuity Objective: the MC-DO gravity field data product should at least meet the GRACE-FO Baseline science requirements on spatial/temporal resolution and accuracy with at least 12 months of overlap between the GRACE-FO and MC-DO to assess potential differences between the two data sets to support calibration and validation efforts

**rationale: we have effectively already encountered a gap of this magnitude (perhaps more considering some degradation in the last year of GRACE operations); assessments of that impact are still underway but we are assuming that it will ultimately be "acceptable". We identified 3 potential impacts of data gaps that should be assessed by the MC team and members of the science community for the 3 primary disciplines: 1) impact on applied science/operational products (e.g., loss of groundwater data), 2) science impact from missing an important geophysical signal during the gap, 3) science/applications impact due to uncharacterized differences in measurement system performance (random and systematic) between GRACE-FO and MC-DO.*

# GRACE-FO Orbit Decay Predictions




Predictions are uncertain.

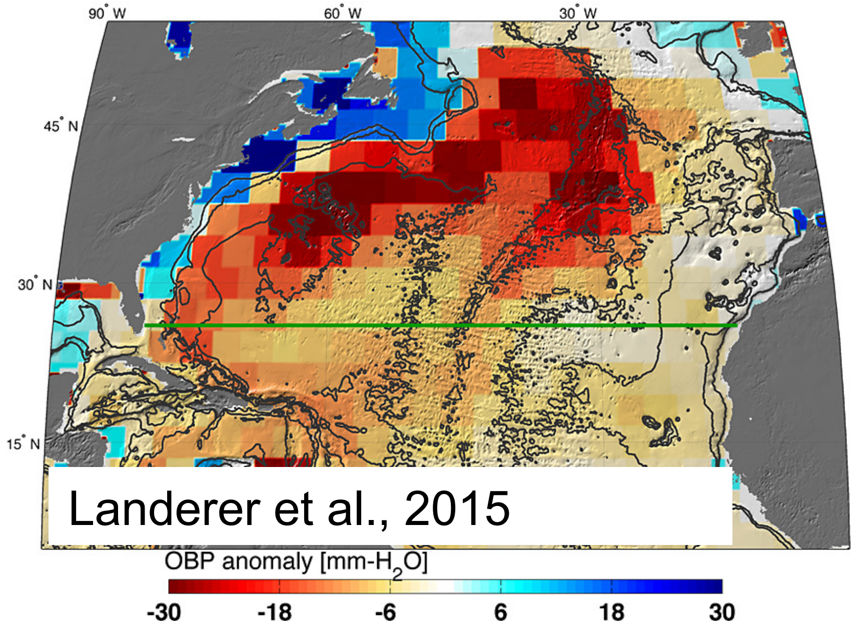
These curves will continue to be updated throughout the course of the study as solar activity evolves.

*Curves courtesy JPL, B. Loomis, J. Chrone – to be updated with latest GFO state vector and solar activity

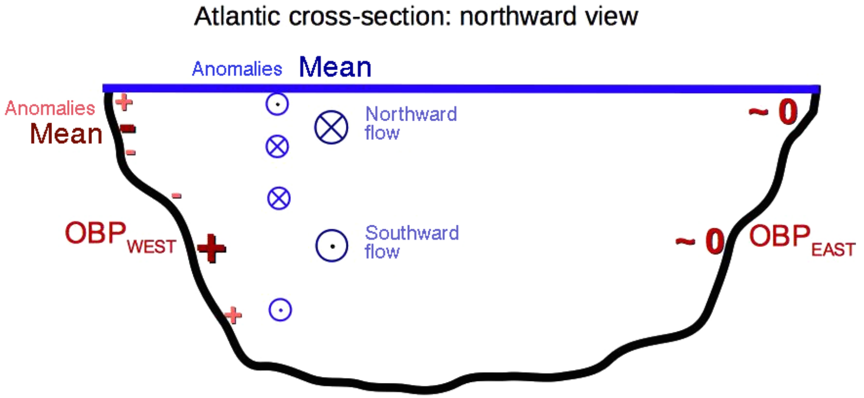
# Decadal Survey: Climate Variability

- QUESTION C-7. How are decadal scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?

    - C-7e. Observational verification of models used for climate projections. Are the models simulating the
observed evolution of the large scale patterns in the atmosphere and ocean circulation, such as the frequency  and magnitude of ENSO events, strength of AMOC, and the poleward expansion of the sub-tropical jet (to a 67% level correspondence with the observational data)? [IMPORTANT]




Landerer et al., 2015




Bentel et al., 2015

# General conclusions

- “Threshold” and “Baseline” should be consistent with the current capability – current capabilities can fulfill all quantitative science targets for climate variability (based on GRACE/GRACE-FO measurement error)
- Continuity and length of time series is most important for determining trends (and accelerations)
- Continuity also means consistency of measurement, quality and ability to achieve performance of GRACE/GRACE-FO
  - Implications for gap analysis and length of overlap

# C.1a+d: Sea Level budget closure

- Global sea level within 0.5 mm/yr and regional sea level 1.5 (6000x6000km2)-2.5 mm/yr(4000x4000km2) (= downscaling of global number) – can be met within measurement uncertainties of current capibilities
- Threshold/baseline should have GRACE/GRACE-FO quality to meet these targets
- Long time series are key – lifetime of architecture above increasing resolution for sea level budget on global and even regional level
- Interannual flucatuation influence trend and acceleration estimates – hence long gaps influence our ability to estimate those
  - Note: architecture concept – if SST – does not require overlap unlike other missions; overlap might be needed though when switching to different architecture type

# C.1b: Ocean heat budget

- Oceanic heat uptake to within 0.1 Wm-2 (*1 mm/yr corresponds to 0.75 W/m2*) ~= 0.13 mm/yr
- GRACE: 0.2 mm/yr measurement uncertainty
- Threshold/baseline can't be less than current capabilities
- Altimetry/GRACE combination needed – independent measurement of heat uptake – constraint on atmospheric observations
- Long time series most important  - longevity of the system or replishable

# C.1c: Ice sheet mass

- Total ice sheet mass change to within 15Gt/yr
- GRACE: 8Gt/yr Greenland, 12Gt/yr – measurement uncertainty
- Threshold/baseline would need to be close to current capability
- Combinations with altimetry key for getting the best of both worlds – spatial vs. temporal resolution
- ‘goal’ could aim at better spatial resolution to fill in for IceSat resolution if that won’t be available at some point (DS recommends taking action for another mission if ice altimeter capabilities are not filled in by other agencies’ POR)

# C.7d-e: Decadal changes in atmosphere and ocean

- Ocean bottom pressure is key variable
- Parameter has low contribution to DS goal
- Key science: deep/mean circulation
- AMOC: current resolution gives some results for some latitudes but topographic changes make it difficult to improve science with any kind of spatial resolution
- BPRs can fill gaps in certain regions but trends not well-defined